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Acoustics and Microphone Placing in Broadcast Studios

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PART I

MUCH of the material in this paper is in no wise new. With the growing complexity of technology, which is both a result and a cause of specialization, it has become almost as serviceable to present a compilation of material collected from one body of workers to another potentially interested group, as to submit original observations and conclusions within a specialized circle. Most of the work in the field of architectural acoustics has been done by physicists for architects. Some of this is of general interest to radio engineers, and of special interest to radio broadcast engineers. With this consideration in view I have gathered together a portion of it in the first part of this paper, without pretending to any originality or even complete understanding of the topic. In the discussion of the specific problems of broadcast studio design and microphone placing which constitute the second and third parts of the paper I have drawn freely on the operating experience of my colleagues in the National Broadcasting Company, especially Messrs. O. B. Hanson, E. F. Grossman, and R. M. Morris of the Plant Operation and Engineering Department.

SECTION I. THE PHYSICS OF SOUND PROPAGATION IN AUDITORIUMS

THE scientific foundations of architectural acoustics were laid by the late Prof. Wallace Clement Sabine of Harvard. A broadcast studio is merely a special kind of auditorium—one in which the nature of the sounds reaching an artificial ear, the microphone, is the principal consideration. Before proceeding with a study of the special problems of broadcasting rooms we shall, therefore, review the general theory of sound distribution in closed spaces. This outline will necessarily be based largely on the work of W. C. Sabine* and his successors.

An auditorium serves the double purpose of giving shelter to a group of listeners and of confining sound, thereby increasing the general level of loudness within the space. In order that hearing may be good for any particular listener the sounds as they reach him must be sufficiently loud, but not too loud; sounds that were discrete at the source must remain discrete or not overlap seriously; and the various components of the speech or music must remain in their true relative proportions, frequency, and wave shape. These requirements cannot be met precisely nor, in practice, is it necessary that they should be. For one thing, the human ear is a rather widely tolerant sense organ. Secondly, the characteristics added by the room may be unobjectionable or pleasant.

Given a source of sound in still air, the wave spreads out spherically, the intensity dropping off according to the inverse square law. This follows from the fact that the area of a sphere is proportional to the square of the radius. As the wave progresses a certain proportion of the sound energy degenerates into heat, owing to the viscosity of the gas. This factor is found to be negligible in practice, so that until the disturbance reaches the walls, in the case of an auditorium or other closed space, the intensity at any point is quite accurately inversely proportional to the square of the distance from the source.

The importance of the boundary conditions in such acoustic enclosures is apparent when it is learned that ordinary hard wall surfaces are better reflectors of sound than the best mirrors are with respect to light. A good mirror reflects about 90 per cent. of the incident light. In the case of a wall of plaster or brick, a sound reflection of over 95 per cent. is the rule. This holds generally for hard substances. In general materials absorb sound in inverse ratio to their density. Soft materials, such as curtains, carpets, cushions, special porous plasters, clothing, and people, therefore have relatively low reflecting efficiency. In such cases the sound is said to be partially absorbed. The term *absorption* is taken as including both the conversion of sound into heat within the body of the material and its transmittal through the structure, since in either case the sound energy is lost to the auditorium. This reduces the acoustic coefficients of the material to two: a coefficient of reflection and a coefficient of absorption, one being the obverse of the other. The coefficient of absorption is con-

*Sabine, W. C.: *Collected Papers on Acoustics.* Harvard University Press, 1923.

veniently taken as the percentage of sound absorbed by a material as compared to an open window of the same area, the latter being a perfect absorber (in reality a perfect transmitter).

When a room contains good reflecting surfaces a large number of reflections, up to several hundred, may be attained before the sound has died down. The results of such multiple reflection, while very complicated in detail, may be summarized as follows:

1. The production, in some cases, of echoes. An echo is defined as a distinct repetition of an original sound.

2. Reverberation, which is the prolongation of an original sound through more or less confused and overlapping reflections.

3. Interference, or the neutralization, which may be partial or complete, of the sound energy at a given point, for a given frequency of vibration, as a result of a rarefaction and a condensation arriving at this point simultaneously by different paths.

4. Resonance, which in acoustics is the integrated response of a vibrating body, or one containing sound vibrations, at its natural period, analogous to electrical resonance in the forms familiar to radio engineers.

5. An increase in general intensity over the value which would obtain were no enclosing structure present. In general, loudness of sound in a room is proportional to the reverberation. Anything which increases reverberation increases the general level of intensity in a room, while absorbents make the space acoustically "dead." General loudness, in other words, is proportional to the reverberation time and inversely proportional to the absorbing power of the materials in the room.

As long as sound comes from an active source, the intensity in different parts of the room will vary greatly. The intensity diminishes, as we have seen, inversely as the square of the distance by an inherent law of the distribution, and is diminished further by absorbents between the source and the point of audition. But very soon after the source has ceased the intensity of the residual sound is practically the same in all parts of the room, since this residual sound undergoes multiple reflections and diffractions in its decay. The failure to differentiate between the states of sustained and decaying sounds has led to considerable misunderstanding of some of Sabine's conclusions. He found, (1) that the duration of audibility is nearly independent of the position of the source of sound, and (2) the efficiency of an absorbent in reducing the duration of audibility of the residual sound is usually nearly independent of the position of the absorbent. This follows from the fact that the viscosity of the air is a negligible factor, so that multiple reflections shortly equalize the distribution of the remaining energy. But in the case of the original sound, as well as for discrete echoes, which approximate the condition of an active source of sound, it is not at all true that the position of absorbents with respect to points of sound generation and audition or electrical pick-up is a matter of indifference.

The decay of sound in a room after the cessation of the source is thus a measure of the acoustic properties of the room and its materials. If the absorption is high the residual sound will disappear quickly; if the absorption is low the period will be correspondingly higher. W. C. Sabine developed an equation connecting the energy present at any instant with the elapsed time and a number of other factors. This expression is

$$E = \frac{Ap}{avV} e^{\frac{-avt}{p}} \qquad (1)$$

where E is the energy of sound per unit of volume in a room at the time
A is the rate of emission of energy from the source
P is the mean free path of sound between reflections
a is the average coefficient of absorption
v is the velocity of sound
V is the volume of the room
t is the time at any instant after the source of sound is stopped.

Recently Watson* has based further work on determination of absorption coefficients of materials on a form of the above expression developed by Jaeger:

$$E = E_0 e^{-kt} = \frac{4A}{avs} e^{\frac{-avst}{4V}} \qquad (2)$$

where s is the total area of surfaces exposed to the sound waves, and p is replaced by its equivalent $4V/s$.

Solving for t we get

$$t = \frac{4V\,2.3}{avs} \log_{10} \frac{4A}{avsE} = \text{Constant} \frac{V}{as} \log_{10} \frac{4A}{avsE} \qquad (3)$$

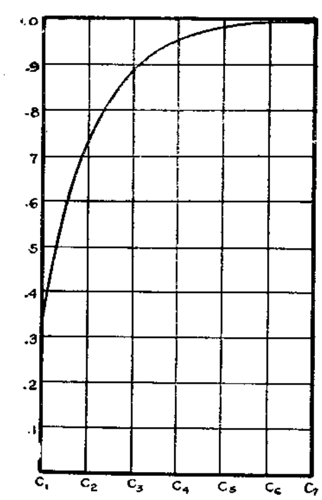

FIG. 1
Absorbing power of an audience at frequencies from 64 to 4096 cycles per second. From W. C. Sabine

The meaning of this is

$$\text{Time of reverberation varies as } \frac{\text{Volume} \times \text{Loudness}}{\text{Absorption}} \qquad (4)$$

for the loudness is proportional to the logarithm of the intensity

$$\left(\log \frac{4A}{avse}\right)$$

If E is given a value of unity, corresponding to the threshold intensity, (3) may be rewritten

$$t = \frac{4V\,2.3}{avs} \log_{10} \frac{4A}{avs} \qquad (5)$$

*Watson, Floyd R. *The Absorption of Sound by Materials*, University of Illinois, Urbana, Ill., 1927.

These equations, connecting t with a, suggest methods of determining absorption coefficients of materials when A, the rate of emission of sound, can be measured. In actual laboratory determinations various precautions are necessary, such as taking into account the acoustic interference pattern in the room, a difficulty which is overcome in one procedure by periodically varying the test frequency within narrow limits, moving the source of sound, and using a receiving instrument which will give an average response to the variations. Another method of determining absorption coefficients utilizes, instead of a room, standing waves set up in a long tube, stopped at the far end with absorbing material. Watson, in his latest work, used mainly the room method devised by W. C. Sabine, but took advantage of apparatus, such as audio beat oscillators in place of organ pipes as emitters, which was not available in Sabine's time. Some of the coefficients resulting from this work are as shown in Table 1.

The coefficient of absorption at a given pitch, such as 512 cycles, will not hold, in general, for other frequencies. The figures contained in Table 2 taken also from Watson, although not all due to him, show the variation of the coefficient with frequency for a number of materials, over a range of 5 octaves:

Fig. 1, taken from W. C. Sabine, shows the variation of the absorbing power of an audience with frequency.

The marked dependence of absorption on pitch is an important factor in audition and reproduction of music. The fundamental sounds of music fall, in general, between 30 and 5000 cycles per second. Some of the ranges, in physical pitch, are as follows (Table 3):

TABLE 3

	Range, Cycles
Human voice, *bass* (very low)	60–340
baritone	90–390
tenor	128–480
alto	170–680
soprano (very high)	240–1300
String instruments, *bass viol*	40–240
'cello	64–680
viola	128–1150
violin	190–3070
Percussion instruments, *piano*	26–4096
kettle drums	85–170
Wind instruments, *bass tuba*	42–340
bassoon	60–480
bass clarinet	80–480
trombone	80–480
French horn	100–850
trumpet	160–960
clarinet	160–1540
oboe	250–1540
flute	250–2300
piccolo	500–4600
organ (extreme range)	16–16000

TABLE 1

SOUND ABSORPTION COEFFICIENTS FOR PITCH 512

Material	Coefficient
Open window	1.00
Akoustolith (artificial stone)	0.36
Balsam Wool, bare, 1″ thick, 0.26 lb. per sq. ft.	0.44
Brick wall	0.032
Brick wall, painted	0.017
Carpet, unlined	0.15
Carpet, lined	0.20
Acousti-Celotex, type A, unpainted	0.25
Acousti-Celotex, type B, painted or unpainted	0.47
Acousti-Celotex, type BB, painted or unpainted	0.70
Acousti-Celotex, type C, painted or unpainted	0.30
Armstrong Cork Board, 1″ thick, 0.87 lb. per sq. ft.	0.30
Cork tile	0.03
Curtains in heavy folds	0.40–0.75
Flaxlinum, bare, 1″ thick	0.61
Glass	0.027
Hairfelt, bare, 1″ thick, 0.75 lb. per sq. ft.	0.58
Linoleum	0.03
Marble	0.01
Nashkote A, $\frac{1}{2}$-inch thick	0.31
Nashkote A, $\frac{3}{4}$-inch thick	0.41
Plaster on wood lath	0.034
Sabinite Acoustical Plaster	0.21
Ventilators	0.75
Wood, plain	0.06
Wood, varnished	0.03
Individual Objects	
Adult person	4.7
Plain wood seats	0.15
Church pews, per seat	0.2–0.5
Seats, upholstered seat and back	0.75–2.00

Sabine discusses the effect on musical balance of variation in absorption with pitch in the following passage:

"Given a room comparatively empty, with hard wall surfaces, for example plaster on tile, and having in it comparatively little furniture, the amount of reverberation for the sounds of about the middle register of the double-bass viol and for the sounds of the middle register of the violin will be very nearly though not exactly equal. If, however, we bring into the room a quantity of elastic felt cushions, sufficient, let us say, to accommodate a normal audience, the effect of these cushions, the audience being supposed absent, will be to diminish very much the reverberation both for the double-bass viol and for the violin, but will diminish them in very unequal amounts. The reverberation will

TABLE 2

Material	Coefficient						Authority
Pitch =	128	256	512	1024	2048	4096	
Open window, theoretical	1.00	1.00	1.00	1.00	1.00	1.00	
Akoustolith tile, 1″ thick	0.06	0.12	0.36	0.52	0.52	0.36	W. C. Sabine
Akoustolith plaster ½″ thick on ¼″ lime mortar	0.21	0.24	0.29	0.33	0.37	0.42	C. M. Swan
Rumford tile, 1″ thick	0.09	0.18	0.29	0.34	0.34	0.30	W. C. Sabine
Ambler sound absorbing plaster	0.03	0.06	0.14	0.17	0.19	0.11	Watson
*Asbestos-Akoustikos felt, ¾″	0.18	0.30	0.54	0.64	0.63	0.57	Swan
**Nashkote A, ¾″	0.19	0.28	0.41	0.43	0.39	0.32	Swan

*A mixture of hairfelt and asbestos, bare.

**Asbestos-Akoustikos felt with muslin cloth cemented to the felt and a special paint applied.

now be twice as great for the double-bass as for the violin. If an audience comes into the room, filling up the seats, the reverberation will be reduced still further and in a still greater disproportion, so that with an audience entirely filling the room the reverberation for the violin will be less than one-third that for the double-bass. When one considers that a difference of five percent. in reverberation is a matter for approval or disapproval on the part of musicians of artistic taste, the importance of considering these facts is obvious.

Sabine then recalls the fact that the average loudness of a sound in a room is proportional inversely to the absorbing power of the material in the room, and continues:

> . . . if the double-bass and the violin produce the same loudness in the open air, in the bare room with hard walls both will be reinforced about equally. The elastic felt brought into the room would decidedly diminish this reinforcement for both instruments. It would, however, exert a much more pronounced effect in the way of diminishing the reinforcement for the violin than for the double-bass. In fact, the balance will be so affected that it will require two violins to produce the same volume of sound as does one double-bass. The audience coming into the room will make it necessary to use three violins to a double-bass to secure the same balance as before.

Equally significant, of course, is the effect of varying absorption on the overtones which lend characteristic quality to the various musical instruments. These overtones, which in the field of sound may be both exact multiples of the fundamental (harmonics), as in alternating current generation, or inharmonic partials in other cases, go up to above 10,000 cycles per second for the human voice, and correspondingly in the sounds of instruments. While a 100–5000-cycle band gives good reproduction and is the present standard in broadcasting, the scale is constantly being extended with the aim of securing quality as close to the natural as possible, and wire line cut-offs and other limiting factors are being adjusted with this end in view. A flat transmitting band of seven octaves, say 50–6400 cycles, with gradual tapering off at the sides, is the immediate objective. The effect of absorbing surfaces in this frequency band is obviously of consequence in the design of broadcast studios, and it is probable that the future trend of design will be increasingly toward flat absorption in the studio as well as flat transmission in the electrical circuits.

The optimum period of reverberation of a room depends on the use to which it is to be put. For speech, the lowest reverberation consistent with comfortable loudness is to be desired, inasmuch as reverberation can only give rise to confusion through overlapping syllables, without adding anything of value to the sounds of speech. For musical rendition, on the contrary, there are optimum periods on which musicians agree quite definitely. For piano music in a room a figure of 1.08 seconds for the optimum duration of audibility was established by W. C. Sabine. P. E. Sabine* says, "The time of reverberation for an auditorium with its maximum audience . . . should lie between one and two seconds. For speech and light music it should fall in the lower half of this range, while for music of the larger sort, it may be nearer the upper limit." A bulletin of the Philadelphia Bell Telephone Company gives the following values:

TABLE 4

SUGGESTED REVERBERATION IN SECONDS AT 512 CYCLES PER SECOND

Auditorium	Public Address	Speech Input
Small music room or studio	1.0	0.70
Medium theater	1.3	1.0
Large lecture room	1.8	1.4
Large music hall	2.3	1.7
Cathedral	3.0	2.3

These values seem somewhat high for speech. It will be noticed that for speech input purposes the optimum period is here considered to be about three-fourths of that deemed best for an audience in the room, on the theory that secondary reverberation at the place of reproduction will make up the difference.

As the observation of the rate of decay of sound in a room may be used to establish the coefficients of absorption

*Sabine, P. E.: "Acoustics in Auditorium Design," *Am. Architect*, June 18, 1924.

of materials, the process may be reversed and the period of the room calculated, when the volume, the materials, and their coefficients, are known. The formula generally used is*

$$t = \frac{0.05V}{A} \qquad (6)$$

where t is the reverberation time in seconds
V is the volume of the room in cubic feet
A is the total absorption of the room, the sum of the component absorptions. It is calculated by multiplying the area of each type of material by its coefficient of absorption and adding the figures thus obtained.

*A very useful reference article in calculating reverberation coefficients and generally as an exposition of auditorium design is *Circular No. 300* of the Bureau of Standards, on "Architectural Acoustics," Government Printing Office, 1926.

A typical set of calculations of the reverberation time of a room, showing how this factor may be altered within wide limits, is given below:

TABLE 5

Room Dimensions, 51′ by 36′ by 20′
Volume, 36,700 cubic feet

MATERIALS

Floor	*Ceiling*	*Walls*	t in seconds at 512 cycles
Linoleum	Plaster on tile	Plaster on tile	9.66
Linoleum	½ Plaster ½ Celotex D	½ Plaster ½ Celotex D	2.32
½ Linoleum ½ Carpet rug	½ Plaster ½ Celotex D	Celotex D	1.58
Carpet	½ Plaster ½ Celotex D	Celotex D	1.39
Linoleum	Celotex D	½ Celotex D ½ Curtains over plaster	1.00
Linoleum	Celotex D	Curtains over ½ Celotex D and ½ plaster	0.81
Carpet	Celotex D	Curtains over ½ Celotex D and ½ plaster	0.71

Coefficients used in calculation:

Linoleum	0.03	
Plaster on tile	0.025	
Celotex D ($\frac{7}{16}$″ thick, no perforations)	0.25	
Curtains over plaster	0.50	
Curtains over Celotex D	0.50	(Assumed)
Carpet rug	0.20	

Actually, the combination of curtains over an absorbing material probably gives a considerably higher coefficient than 0.5, but in the calculation above it happens that it was desired to balance this against the probable reflection from a number of hard surfaces (pianos, a window, etc).

The prevention of echoes in auditoriums has not been discussed, since the scope of this paper is not intended to include a complete treatment of the design and possible defects of such rooms. It should be said, however, that as the reflection from a light mirror may be broken up by scratching the surface of the mirror, in acoustics an analogous device is used, reflecting walls of hard material being coffered with the object of breaking up echoes into reverberation. Depressions about four feet wide and about ten inches deep are said to give the best results with the wavelengths normally encountered in the human voice.

SECTION 2. REVERBERATION TIME OF BROADCAST STUDIOS

THERE are obvious differences between an auditorium and a broadcast studio. In the former case it is desired to provide sounds with the proper characteristics for an audience, which usually fills the major part of the floor and galleries, and if the auditorium is to be effective, hearing must be good over this considerable area. In the case of a broadcast studio, conditions throughout the room are of no special consequence as long as an undistorted wave pattern may be secured at the point of pickup. Furthermore, this electrical receptor may be placed relatively close to the instruments. The audio amplifiers of the broadcasting station then being adjusted to the proper "gain," good audio reproduction will be secured even though the sounds reaching the microphone are too loud for comfortable listening at this point. As a result, reverberation probably plays less part in the action of a broadcast studio than in the average auditorium. With the microphone placed relatively close to the instruments, the directly received sounds predominate and the prolongation and reinforcement due to reverberation become less noticeable.

When the technique of broadcasting began to be developed in about 1921, most of the material outlined in the foregoing section was available and was soon utilized by the engineers in charge of broadcast studio design. The tendency naturally was to over-apply the principles involved, sometimes quite radically. Absorption was carried to a point where it interfered with the best musical rendition, the artists being forced to perform under unnatural conditions. As a secondary defect, the absorption at the higher frequencies was excessively out of proportion, tending to drop out the upper register right at the start. Inasmuch as the radio receivers of the time did not pass either low or high notes, but only the two or three middle octaves, this defect went unnoticed.

A not atypical studio of the early period was one of the following design:

TABLE 6

Studio Dimensions, 30′ by 20′ by 9′
Volume, 5,400 cubic feet

	ABSORPTION
Floor (600 sq. ft.) covered with carpet (coeffi. 0.25)	150.
Ceiling (600 sq. ft.) covered with hair felt (coeff. 0.50)	300.
Walls (900 sq. ft.) draped with monk's cloth curtains (coeff. 0.50)	450.
TOTAL ABSORPTION	900.

Period of reverberation at 512 cycles, by Formula (6): 0.30 seconds, approx.

(*To be continued in the June issue*)